(4)

A TRIDENT SCHOLAR PROJECT REPORT

NO. 168

Development of a Taction System Using Piezoelectric Film

UNITED STATES NAVAL ACADEMY
ANNAPOLIS, MARYLAND

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER U.S.N.A. - TSPR; 168 (1990)	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE *(and Subtitle)* DEVELOPMENT OF A TACTION SYSTEM USING PIEZOELECTRIC FILM.		5. TYPE OF REPORT & PERIOD COVERED Final 1989/90 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Lyle E. Hoag		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS United States Naval Academy, Annapolis.		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS United States Naval Academy, Annapolis.		12. REPORT DATE 22 May 1990 13. NUMBER OF PAGES 58
14. MONITORING AGENCY NAME & ADDRESS *(If different from Controlling Office)*		15. SECURITY CLASS. *(of this report)* 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

This document has been approved for public release; its distribution is UNLIMITED.

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

18. SUPPLEMENTARY NOTES

Accepted by the U.S. Trident Scholar Committee.

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

Plastic films
Piezoelectric materials
Tactile sensors
Robotics

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

The piezoelectric properties of materials such as naturally occurring quartz have been used in pressure and vibration sensors for many decades. Over the last twenty years synthetic crystals have been developed with improved mechanical properties and improved machinability over naturally occurring quartz. A more recent development is a plastic film which displays the piezoelectric property. The film is finding
(OVER)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-LF-014-6601

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

application in areas where crystals would be impossible or difficult to use beaause of its flexibility and ruggedness as compared to quartz. A taction system is a multi-sensor touch sensing system. A taction system was designed using piezoelectric film. Digital signal processing techniques were used to acquire and display the voltage produced by an array of sixteen tactile sensors. It was demonstrated that the taction system could be used in a variety of applications requiring multiple pressure measurements such as touch sensing in robotics and in prosthetic devices.

U.S.N.A. - Trident Scholar project report; no. 168 (1990)

Development of a Taction System Using Piezoelectric Film

A Trident Scholar Project Report

by

Midshipman Lyle E. Hoag, Class of 1990

U. S. Naval Academy

Annapolis, Maryland

Robert S. Reed

Associate Professor Robert S. Reed
Systems Department

INSPECTED 4

Accepted for Trident Scholar Committee

Dennis F. Hasson

Chairperson

22 May 1990

Date

Accession For	
NTIS GRA&I	☑
DTIC TAB	☐
Unannounced	☐
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	

USNA-1531-2

Abstract

The piezoelectric properties of materials such as naturally occurring quartz have been used in pressure and vibration sensors for many decades. Over the last twenty years synthetic crystals have been developed with improved mechanical properties and improved machinability over naturally occurring quartz. A more recent development is a plastic film which displays the piezoelectric property. The film is finding application in areas where crystals would be impossible or difficult to use because of its flexibility and ruggedness as compared to quartz.

A taction system is a multi-sensor touch sensing system. A taction system was designed using piezoelectric film. Digital signal processing techniques were used to acquire and display the voltage produced by an array of sixteen tactile sensors. It was demonstrated that the taction system could be used in a variety of applications requiring multiple pressure measurements such as touch sensing in robotics and in prosthetic devices.

Acknowledgments

Research is rewarding, and I am grateful to the United States Naval Academy for giving me the chance to spend my time doing meaningful work that will benefit future students at the Naval Academy. Research is not a one-man effort, and certainly this Trident project was not. Foremost, I acknowledge Associate Professor Robert S. Reed, my Trident Advisor. Professor Reed was instrumental in helping me to complete the project. Often my ideas of different design modifications would have taken longer and proved less fruitful without his assistance. His experience with research convinced me to labor to keep designs as simple as possible. He helped me to realize that in research, for every problem for which the researcher is prepared, ten more problems arise for which he is not prepared. I thank the entire Systems Engineering Department faculty for their help in so many different problems that I cannot list them all. To Clyde Atwell and Sam Hawkins, I give my thanks and respect; any technicians who can put up with not only my requests but those of 90 other system engineers deserve at least that. I also thank the United States Naval Academy Library for help in compiling information concerning piezoelectricity and taction systems and the Chemistry Department for help in getting some of the raw materials needed to complete this Trident Project. Lastly, I would like to thank LT L.T. Evans of the English Department for his assistance in helping me edit this Trident Project Report.

Table Of Contents

List of Figures

Introduction

Piezoelectricity, the production of a voltage when a force is applied, is caused by placing a mechanical strain on particular crystals. The converse is also true; an applied voltage will cause the piezoelectric crystal to vibrate. Piezoelectric crystals are quite useful for sensing or transducing mechanical vibration and pressure. Until recently, piezoelectric material that could be shaped and easily machined was not available. However, Polyvinylidene fluoride (PVDF), a new polymer that can be made into a thin film, shaped, and cut to fit almost any surface, has piezoelectric properties.

Touch sensing is the ability to measure the applied force when contact is made with a sensor. Multiple tactile sensors have the capability of describing the outline of an object. This capability is called taction. Both robotics and prosthetics can benefit from the use of taction systems, because delicate and complex tasks that do not employ proper sensory feedback are very hard to accomplish. The necessary feedback can be provided with a PVDF tactile sensory array, which has the advantages of compliance and light weight. The tactile sensor would be small enough and flexible enough to adhere to existing structures without changing their operating characteristics [1].

The objective of this Trident project is to develop a piezo film sensor that will be placed in an array to form a taction system. The problem is to design a taction system using PVDF and determine the characteristics of the system. The design and construction phase is broken down into three major stages:

(1) developing appropriate signal conditions to transduce the sensor voltages;

(2) developing computer techniques for representing the sensor voltages;

(3) designing and building the actual taction grid that will be used for testing and calibration.

Problem Statement

A touch-sensing system (taction system) will simulate touch for robots and prostheses. Taction systems are all relatively new; therefore, much work is yet needed to create a comprehensive taction system that can distinguish many different components of touch. The system should be able to distinguish the shape, surface texture, and size of an object; it should determine the force that the object is exerting; and it should measure any possible movement between the object and the end effector.

What distinguishes a good touch-sensing device from a poor one? Harmon polled 47 researchers and manufacturers about taction systems [2]. According to his research, a tactile sensor should:

(1) be rugged and compliant;

(2) process most of the information before communicating with the robot;

(3) not be over 100 mils thick unless job specifications required greater thickness;

(4) detect forces as low as 5 to 10 grams, with a dynamic range of about 1000 to 1;

(5) be stable, monotonic, linear, and not exhibit hysteresis (i.e., be repeatable).

Unfortunately, very few tactile devices satisfy most of those requirements. In addition, no sensor exists that can meet all of these requirements. However, the development of a comprehensive tactile sensor is a small part of the problems associated with taction system development. Taction systems today do not process quickly and efficiently the information they retrieve. Also, the robot must be programmable to enable it to utilize retrieved information most productively. In the case of prostheses, some device must be made to communicate to the wearer of the prostheses. A high level language that will enable the robot to use given information with flexibility is needed; obviously, some sort of artificial intelligence is required. The design of the gripper poses another problem. A gripper with three or more fingers is generally accepted as the future of robot end effectors. However, designing actuators that will be able to drive the gripper is an obstacle not yet overcome. Good taction systems are just one of the problems needing solution in the future of robotics and prosthesis design [3].

Background

The development of taction systems for modern robotics has lagged far behind the development of vision systems. This lag is understandable for touch is the sense most taken for granted. However, as more complex tasks for robots are devised, the need for a comprehensive taction device becomes pressing. For example, one of the most difficult jobs for a robot to accomplish is precise insertion of pegs into tight-fitting holes. This task, easily done by a human, requires either mechanical compliance or taction for a robot. Mechanical compliance is a measure of looseness. If this simple task were perfected in robotics, all assembly jobs could be revolutionized, especially jobs in the electronics industry [1].

Today, vision systems are used much more than touch sensing systems. Vision systems are used in robotic welding and parts assembly, but taction is relatively new [4]. While a vision system has many uses and advantages, it cannot entirely replace a taction system. A vision system cannot give the user a reading on force as a taction system can. A vision system cannot report any information about the force required to pick up an object or to move the object. While vision systems are useful for finding the orientations of objects, taction systems are computationally faster at finding orientation. Also, finding the size and shape of an object can be obtained directly from a taction device with high resolution. Vision systems need physical references to determine an object's shape and size. A vision system can be used for slip detection, measuring movement between the gripper and the object being held; but problems arise from background lighting and illumination, making the detection of slip using vision systems difficult. The detection of slip using taction systems would be less difficult and insensitive to lighting. A taction device is more reliable for slip measurement because the sensor is in contact with the object. Object contact is the most important reason for developing a touch sensor in addition to a vision system. Taction systems give the robot information about the part of the object that is in the gripper. The force data can in fact be used to protect the object or gripper from damage. The orientation, size, and shape of the object within the end effector of the robot is information that the vision system may not be able to determine because of the robot's position relative to the grasped object [4].

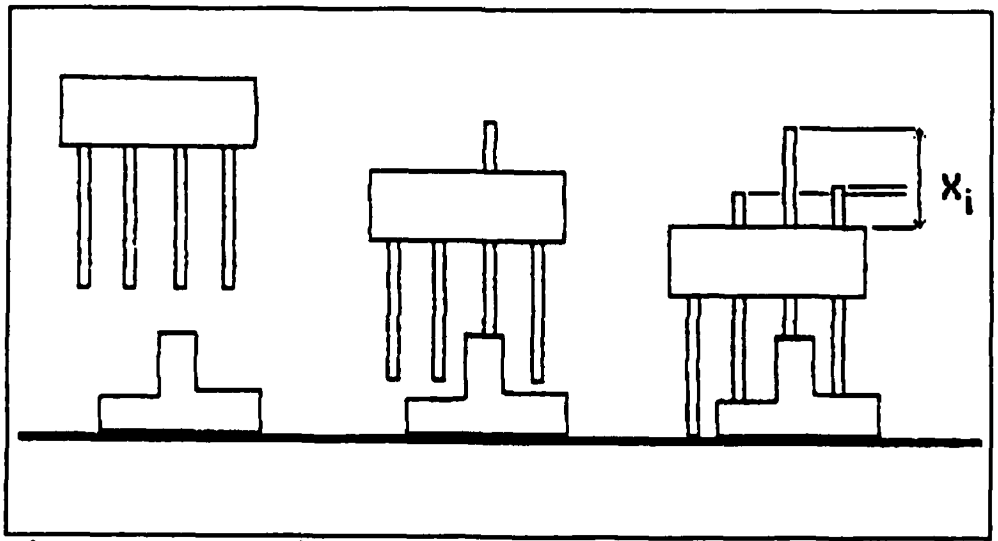

Figure 1: Proximity Rod Tactile Sensor

Many taction systems have been developed besides the one that is to be designed in this project. One of the most basic types of tactile sensor is the proximity rod tactile sensors (see Figure 1). The rods contact the object; the distances the rods are displaced form an accurate two dimensional image of the object. Many rows of this tactile sensor form an accurate three dimensional image of the object. A problem associated with this sensor is that the rods are free to move; therefore, some false deflections may occur. The major problem of a proximity rod sensor is that the size of the rods interferes with the robot's ability to pick up or move the object [4].

Another type of tactile sensor is the photo-detector tactile sensor (see Figure 2), which works on the principles of a "beam breaker." When a force is applied to the elastomer, the size of the beam's path diminishes. The light passing through the path is then collected, and information can be obtained and processed to recover force information. However, two major problems occur in the photo-detector tactile sensors. First, mechanical hysteresis in the elastomer leads to problems with calibration of the tactile array. Hysteresis means the rubber will not return to the original position after a force has been applied. Second, the elastomer has to

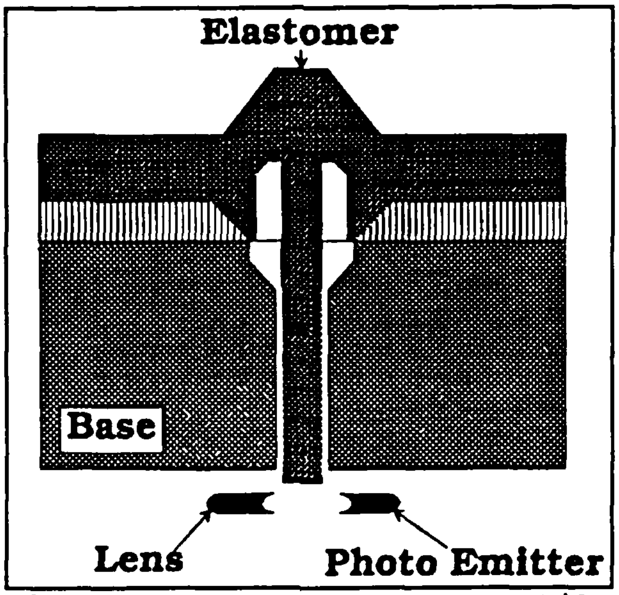

Figure 2: Photo-Detector Tactile Sensor

contact the object to sense a force, yet it needs to be protected from the environment. Furthermore, the complexity and cost of a photo detector tactile sensor are prohibitive to its construction [5].

A new type of tactile sensor is the fiber optic tactile sensor. In this sensor, fiber optic lines underneath the sensor are deformed as force is applied to the sensing pad. In a straight fiber, the loss of light is minimal. As the fiber begins to bend, it loses more light. This loss of light can be measured. Thus, a correlation with the force applied can be obtained. Fiber optic sensing is of great potential use for tactile sensing because fiber optics are cheap, immune to electromagnetic interference, have a large bandwidth, and are immune to "cross talk" (the activation of one sensor by the activation of another sensor). Fiber optic sensors have proven to be linear and very reliable over only a small range of forces - from around 125 grams to 225 grams. The major problem of fiber optic sensors is that experiments with them are not repeatable because of mechanical hysteresis [6].

Yet another type of sensor is a piezo-resistive sensor. A piezo-resistive material's electrical resistance changes as the load on the material is increased. In the force sensing resistor, the relationship is inversely proportional; as the force increases, the resistance decreases. The force-sensing resistor can be made into an array and placed in a voltage divider circuit. The output voltage of the piezo-resistive array can be read with an analog multiplexer. This voltage output is proportional to the force applied. The piezo-resistive sensor, like so many other sensors that actually contact the object, is often not rugged. Above a certain force, the tactile sensor may be damaged, causing insufficient repeatability and problems with noise [7].

The last type of taction system that uses the PVDF is the hybrid piezo-electric tactile system as designed by A. R. Grahn [8]. The major difference between this

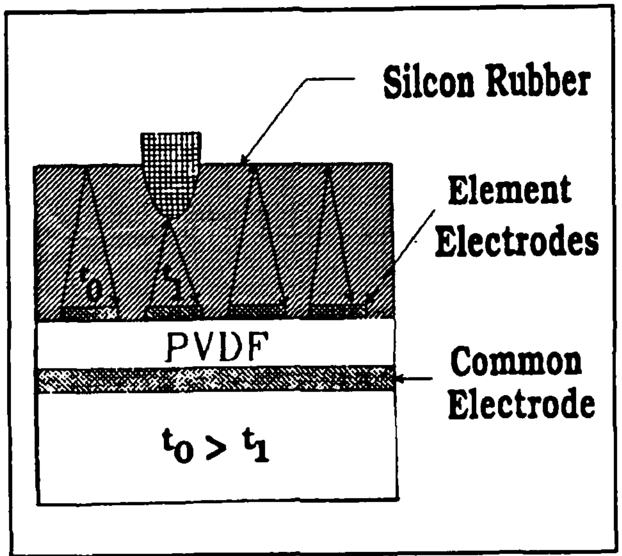

Figure 3: Pulse Echo Tactile Sensor

taction system and the one built in this effort is that PVDF is being used as an ultrasonic transducer instead of force sensor (see Figure 3). The pulse-echo tactile sensor's elements emit an ultrasonic "ping" just as do sonar systems. After the element receives the "ping," the time of flight is calculated and information concerning the shape of the object and the force it exerts can be deduced. This method has many advantages. The pulse-echo sensor can measure force over a 2000:1 dynamic range; it has the spatial resolution of about 0.5 millimeters; and the response time of the film is around 5 microseconds. Associated with this sensor, however, are problems linked to mechanical hysteresis of the silicon rubber. As the silicon gets older or changes temperature, the acoustic properties of the silicon change and thus the time of flight changes [8].

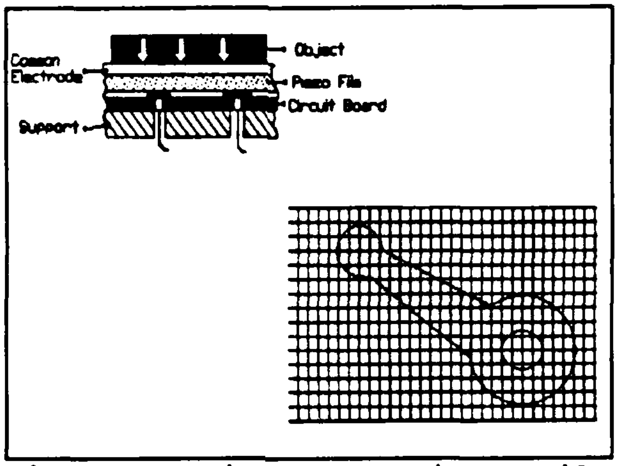

Figure 4: Piezo-Electric Tactile Sensor

The taction system chosen is similar to the piezoelectric system designed by P. Dario (see Figure 4). In Dr. Dario's design, a thin sheet of PVDF is used and bonded onto a printed circuit board. When an object contacts the piezo film, a voltage is induced in the film. The signal can then be processed to determine information about the object [9]. The major disadvantage to this sensor is that the film, capacitive in nature, has no dc response; the film can measure only changes in forces. Fortunately, the time constant of the film is large; the signal takes around 100 seconds to decay completely [10]. The great advantage of the film is that it has many anthropomorphic features, corresponding to human senses. First, it is responsive to both heat and pressure. Second, it has a wide bandwidth, allowing the film to distinguish between a wide range of forces. Surface textures can be distinguished using this type of sensor.

Taction System Design

The taction system designed consists of a piezoelectric polymer (PVDF) tactile sensor, amplifiers, and an analog to digital converter connected to a computer (see Figure 5). The tactile sensor is a 4 X 4 grid (16 channels) used to detect force applied to the pad. The amplifiers take the voltage signal from the elements in the taction pad and convert those signals to ones that are usable by the computer. The A/D converter changes the analog voltage to a number. The computer, through programming, uses these numbers in calculations

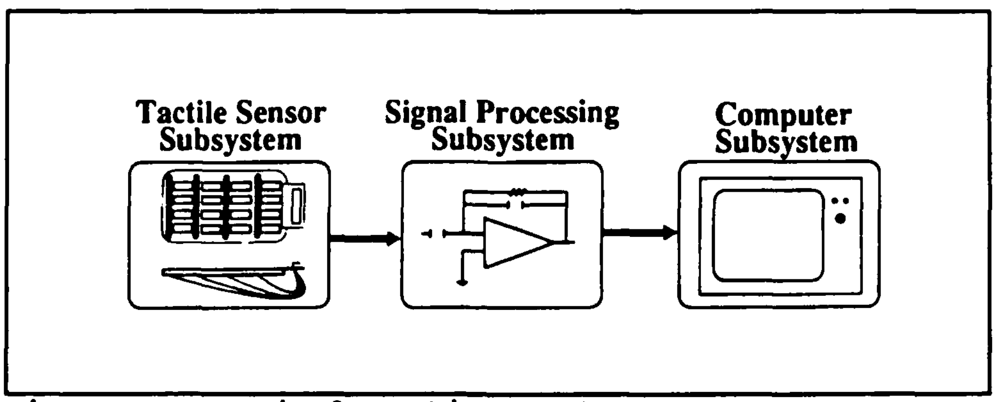

Figure 5: Typical Taction System

so that information concerning the detected force can be shown to the user. Through programming it is possible to show the shapes of the objects and to get an accurate measurement of force.

The design of the taction system had three stages. In stage one, a one-cell tactile sensor was used. The major function of the first stage was to improve techniques for designing and building the amplifiers. The first-stage device verified mathematical models of the film-amplifier system by comparing computer-generated models to experimental results. The models were tested in Matlab [11], a program used to simulate mathematical systems. The purpose of the second-stage taction system was to research the problems associated with multiple signals and the storage of these signals on a computer. To get multiple signals, a tactile grid was used. This grid is pre-manufactured by the Pennwalt Corporation, the manufacturer of PVDF. The major emphasis during the second stage was on computer programming. The third-stage sensor involved designing and building the actual sixteen-element tactile array. The last part of the project was spent testing and calibrating the system and designing a simple task for the taction system to perform.

This taction system design is broken down into three subsystem designs: the computer subsystem, the amplifier subsystem, and the tactile sensor subsystem.

Tactile Sensor Subsystem

The tactile sensor is the heart of a taction system. This design is a sixteen-element array of PVDF capable of distinguishing very basic elements of touch. PVDF was chosen because of the qualities that make it ideal for touch sensing. Like quartz, PVDF produces an electric signal when pressed. However, when quartz is squeezed, its geometry makes it easier for some positively charged atoms to move more readily than other atoms in the quartz. This process sets up a net charge distribution that causes a voltage to be induced. However, PVDF is polarized while it is made. The polarization process is one in which the film is subjected to a large electric field during the melting of the film. This process causes the atoms in the film to align (see Figure 6). When the film is compressed, the voltage induced is by capacitive means, not by any restricted movement in the geometry of the atoms [12]. If a force is applied to the film, its volume and net charge distribution change; as a result, voltage is induced into the film. PVDF also may be used to detect temperature. Heating of PVDF

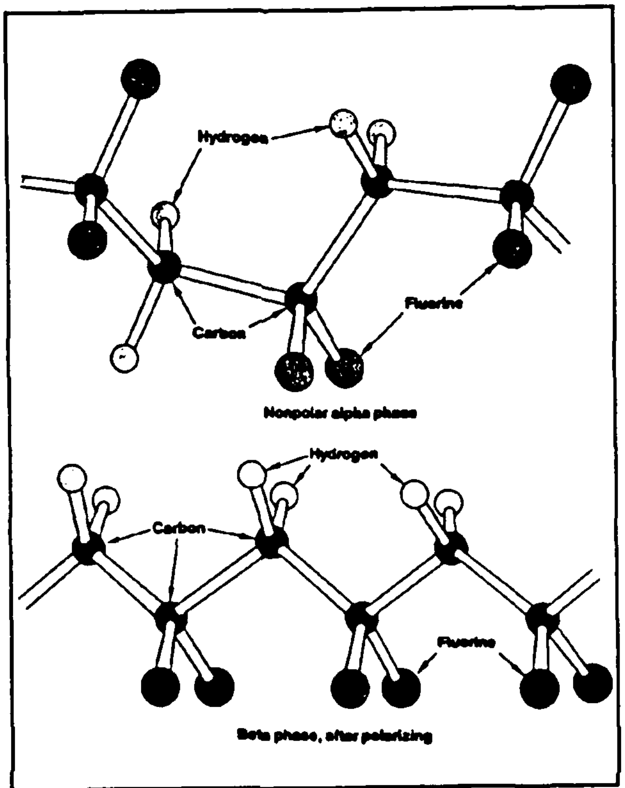

Figure 6: Crystalline Forms of PVDF

causes the expansion of the film, which in turn changes the film's volume and its net charge distribution. Piezo film is anisotropic: the voltage that is induced varies with the direction and orientation of the force applied. Its anisotropy allows the film to be used as a strain gauge. Relative velocity between the sensor and the object can be measured by observing the various voltage outputs that occur at different speeds from the sensor. These properties make PVDF film uniquely suited for a comprehensive tactile sensor. With appropriate signal processing and computer programming, information concerning force, pressure, shape, velocity, and temperature of an object can be retrieved [1].

Since PVDF film is so sensitive to many different kinds of inputs, it must be shielded. A few precautions such as using coaxial cables and shielding the film are necessary for good results. These precautions will alleviate the noise caused by electro-magnetic machinery. Another concern is to shield the taction device from undesired effects of heating. While in some instances detection of heat is wanted, in most taction systems heat detection is not necessary. Placing a thick insulating protective sheet over the PVDF film would be an easy method to solve this problem. Any changes in temperature would be so gradual as not to produce detectable voltage.

The engineering work of this project is supported by mathematical models of a system. Two models for the film are shown below and the mathematical verification of these models is described in Appendix 1.

For these models, the corresponding frequency response of the film is shown in Figure 7. This plot shows that the film has no response to a DC input, meaning that the signal produced by any constant force will eventually decay and go to zero. This property is both good and bad. The positive side is that the film can be stretched and molded to any object, and given time the voltage

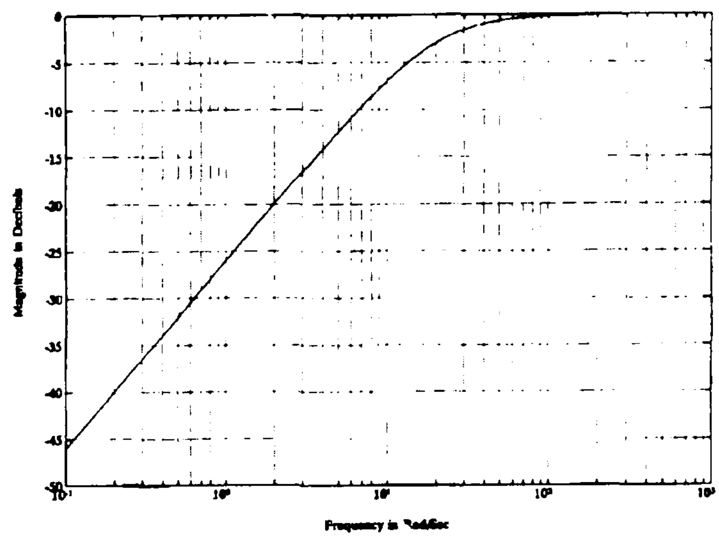

Figure 7: Typical Frequency Response of Film

output will go to zero. The negative side is that because the voltage dissipates over time, accurate force-voltage relationships are more difficult to determine.

Before the tactile subsystem could be completed, two major problems became evident: first, how to etch the film to make separate individual cells; second, how to attach the electrode to the cells. Both had to be done without destroying the thin (28 micro-meter) film. Obviously standard techniques, like soldering, could not be used successfully on this film.

User Etching Of Film

The first technique employed to etch the film was simply cutting the film into individual units, thereby electrically isolating the cells from each other. A problem occurred in that the film was so thin the act of cutting the film would put metal on the edge of the separate cells. This would effectively ground out the cell and make it useless. If the cutting was done with precision, grounds would often not appear at first, but any pressure around the edges of the cell would cause the cell to ground out. This cutting technique could not be used by itself but was used successfully with another technique.

The second technique for etching the film is similar to electroplating. First the film was laid on a sheet of metal. This sheet is attached to one terminal of a DC power source. The other terminal is connected to a pointed object, either a needle or the end of a wire. The power supply is then turned on. By placing the point on the area of the film that needs to be etched, the path for current flow is completed, and arcing at the point of contact occurs. This arcing causes the vaporization of the metallization on the film [13]. This process worked best with voltages from 10 to 14 volts. The major problem with this technique was that the arcing caused melting and scoring of the thin film. This technique might prove more successful for a thicker film but was not be successful with the relatively thin films used in the project.

The third etching technique was the application of sodium hydroxide to remove the metallization. This technique worked best. The metal was removed, leaving unharmed polymer. By using sodium hydroxide, the pattern of the grid could be etched on the film, or the separate elements could be cut and the edges of the separate elements treated in the sodium hydroxide to keep the elements from grounding out. Only one problem occurred with using the sodium hydroxide: the application. The film is very susceptible to degradation caused by the contact with caustic materials. The sodium hydroxide could be applied only to the part of the film that needed to be etched. Application to the part of the film being used as the sensor would cause poor piezoelectric response of the film.

Lead Attachment

The next design problem encountered was the attaching of leads to the piezo film. Leads are attached to the film to read the voltage induced in each cell. The lead attachment should have characteristics to compliment the characteristics of the film. For instance, the film is very flexible; attachment methods should not decrease the flexibility of the film. For the application of a multi-element taction system, low area of attachment is important. The attachment method cannot have a large profile because in its final application it will have to be inserted into the end effector of a robotic system. Also, the mechanical strength should be great enough to survive the environment of the robot. Lastly, speed and ease of application are important, especially if all the robots at the Naval Academy are to receive this taction system.

The first attachment method tried involved pre-made sensors with leads from Pennwalt Corporation. This proved to be the easiest, and it eliminated the problem of user etching the film. But the sensors were larger and bulkier than needed. This size problem would make it practically impossible to make a multi-point taction system that could be installed on the robotic systems at the Naval Academy. The pre-made sensors were also relatively expensive when compared to film in bulk. Additionally, the cost of custom made sensors to the specification needed by the robotic systems at the Naval

Academy would be prohibitive and would deny students a chance to work and learn from designing their own tactile sensors.

Penetrative methods for attaching the film were not used. Penetrative techniques require puncturing the film and then putting either small rivets, nuts and bolts, or eyelets in the film [13]. This procedure would cause the same problem that cutting the film caused.

Many non-penetrative methods were analyzed. The first method tried was mechanical clamping. In this system the film is clamped between two conductive surfaces. The major difficulty was that this method was cumbersome and therefore not very good for the application in robotic systems at the Naval Academy. The second non-penetrative technique was conductive tape. Conductive tape's greatest advantage is ease of use and slim profile. But the area on which the tape had to be applied for good adhesive contact was too large and therefore prohibitive for use in robotic systems. The next method was conductive epoxy. Conductive epoxy could be used to glue the lead directly to the cell. Other advantages included low profile and low area. Disadvantages to using epoxy are long cure time and poor application qualities. The epoxy developed most of its properties a full day after application and the epoxy required three days to cure entirely. Also, the epoxy was messy and not accurate enough to make attachment to a small grid possible. Further, the conductive epoxy must be spread evenly across the film because varying thickness of epoxy causes problems with voltage output of the film. It is therefore necessary to make the epoxy coating the same thickness as the coating on the other cells. Silkscreening the glue would show the best results, but that technique was not available at the time of construction. The best results were from the combination of conductive tape and epoxy. Here the tape or foil is used to squeeze the epoxy as flat as possible. Conductive tape also helps in the application of the epoxy. Small amounts of epoxy can be added to the conductive tape and then applied to the film.

Tactile Subsystem Designs

The first tactile sensor designed was a 4 X 4 tactile array using pre-made 40 mm X 15 mm tactile sensors with pre-attached leads made by Pennwalt corporation (see Figure 8). The sensors were attached to a 7 inch X 5 inch metal plate. The major purpose of this design was to make a reliable multiple channel tactile device to work out any bugs in the signal processing

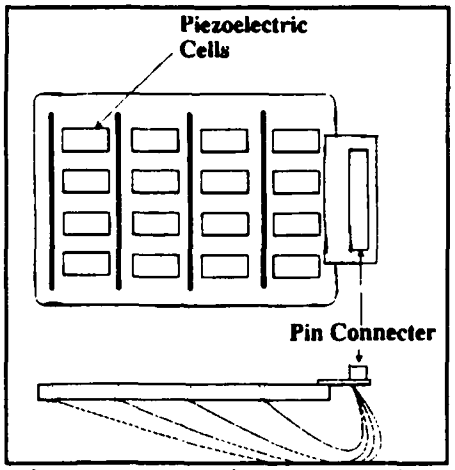

Figure 8: First Tactile Sensor Design

subsystem and the computer subsystem.

The next prototype tactile design was a PVDF sandwich made between a piece of conductive and nonconductive rubber. This design was the end-product of all the work that went into user etching and lead attachment (see Figure 9).

The PVDF was etched using a 6 molar solution of sodium hydroxide. Leads were attached using only the conductive epoxy. The major problem with this design was

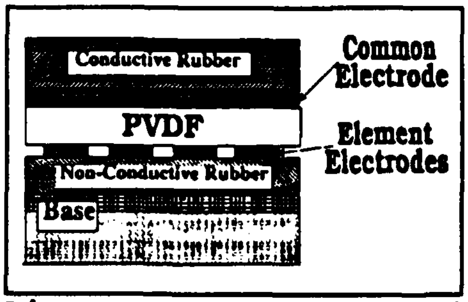

Figure 9: Cutaway of Prototype Tactile Sensor

its bulkiness. This problem could be alleviated by using thinner pieces of conductive and non-conductive rubber. Another problem is that the flexibility caused by the rubber sandwich allows the film to bend in any direction. The film's being anisotropic creates a problem with the calibration of the device to get accurate force-voltage relationships. Since the cells of the taction device are inter-connected, a fair amount of cross-talk occurs between sensors. When one sensor is pushed, all the surrounding sensors are also deformed, causing activation of the surrounding sensors. This cross-talk is not disruptive because the voltages induced in the other cells are smaller than the one in the activated cell. It is possible to produce programming that ignores these signals or uses them to pinpoint the location of the applied force.

The third tactile device made was an industrial version. This was made to show that these devices can be made to be very rugged and able to survive harsh environments. Each element in this array was cut separately, and then the edges were treated using the 6 molar sodium hydroxide solution. Then the epoxy was used in conjunction with metal foil to spread the epoxy evenly and attach the leads. Also, the epoxy was used to attach the ground side of the film to the metal plate.

Lastly, a heavy piece of non-conductive rubber was placed over the film for protection. This tactile device is hardy and easy to calibrate because the voltage is produced only because of compression of the film; there is no bending of the film in any other directions. The first problem with this tactile sensor subsystem is reduced sensitivity, caused by the thick piece of rubber and the sensors rigid attachment to the metal plate. Since the only voltage produced is caused by compression, the voltage tends to be smaller. It is possible to increase the gain in the computer but increased gain multiplies the noise also. The best solution is to use thicker piezoelectric film. This increase in the thickness of the film will cause a corresponding increase in the maximum voltage that can be produced by compression. A step by step instruction on how to build these tactile sensors is included in Appendix 2.

Amplifier Subsystem

Sixteen tactile forcels, elements in a tactile array, were used in the final design. Each force needed to be amplified in some way. A high impedance field effect transistor input amplifier is needed when using PVDF, because the amplifier cancels the effect of the connecting cable capacitance. (See Appendix 1 for a mathematical proof.)

There are three designs for the amplifiers. In the first design, every element has its own charge amplifiers

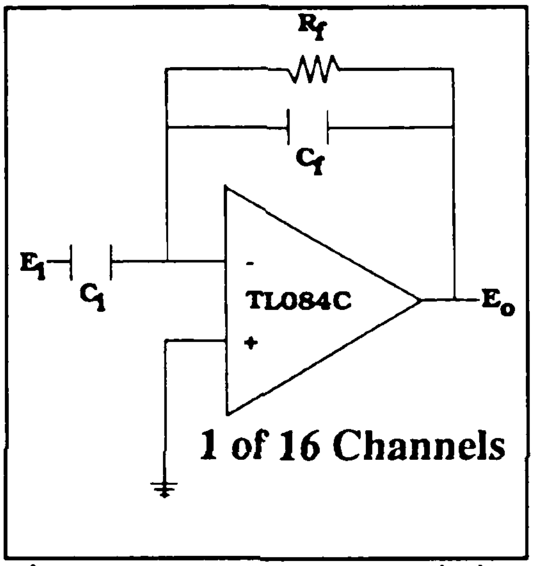

Figure 10: Charge Amplifier

(see Figure 10). One great advantage of this method is that because data can be read in parallel, the method is capable of high speed. Another advantage is that the system is easily built. However, this method of amplifying has three major drawbacks. First, good quality amplifiers are expensive and one amplifier is needed for each channel. Second, the large number of components required would be complex and therefore difficult to test and check for mistakes. Last, any variation in resistors and capacitors in the feedback loop causes changes in the time constant of the film, which in turn would change the force-voltage relations between each element in the tactile array.

The problems of the first design could be solved by multiplexing the output of the tactile sensor subsystem to a single high quality amplifier (see Figure 11). This alternate configuration solves the problems of complexity

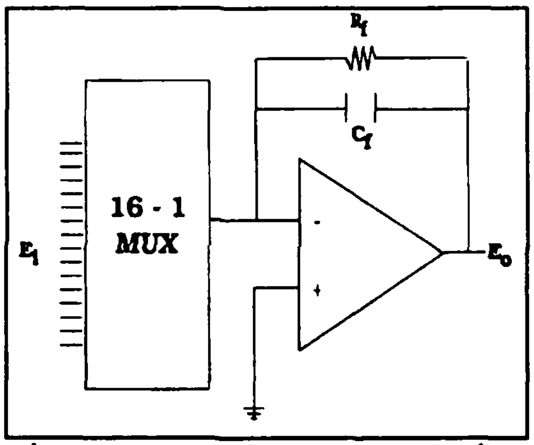

Figure 11: Alternate Design with Multiplexer

at the cost of reduced speed. One large problem with this method is the capacitor-resistor combination in the feedback loop. This feedback type cannot be used with the multiplexer design because the capacitor in the feedback loop stores charge. This charge would act as a memory among elements. Therefore, any activation on one cell would make the cells examined later appear to be activated also. This process of bleed-over charging would continue until the charge on the capacitor had been bled by the resistor.

The solution to this third problem is removal of the resistor from the feedback loop and the addition of the reed switch (see Figure 12). The computer, multiplexer, and reed switch all have to be triggering simultaneously,

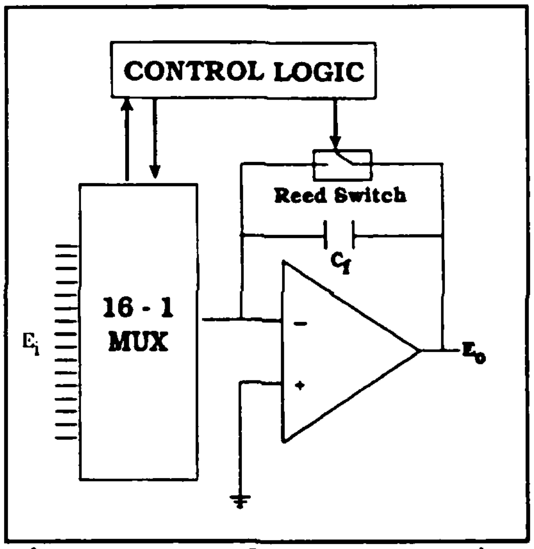

Figure 12: Alternate Design with Reed Switch

or in the order of reed switch, multiplexer, and computer; triggering sequence is an important fact that cannot be overlooked. This sequencing leads to extensive control logic. Minimal control logic is a great advantage of a taction system. Another problem is that a capacitor must be charged before an accurate reading of voltage can be produced. The program must wait until the capacitor is charged. This delay makes the computer programming technique much more difficult and slower. Also, the voltage information could not be as readily changed to force information. Therefore, the first method of separate amplifiers for each channel was used with the best amplifiers available, the TL084C [14]. The calculation of the transfer function of the charge amplifiers with the resistor-capacitor feedback loop and charge amplifier with a capacitor and reed switch feedback loop is derived in Appendix 1.

In the resistor-capacitor feedback combination, a problem arises in optimizing the gain and the time constant. The capacitance of the film cannot be changed and is very small (in the order of 10^{-10} farads). The

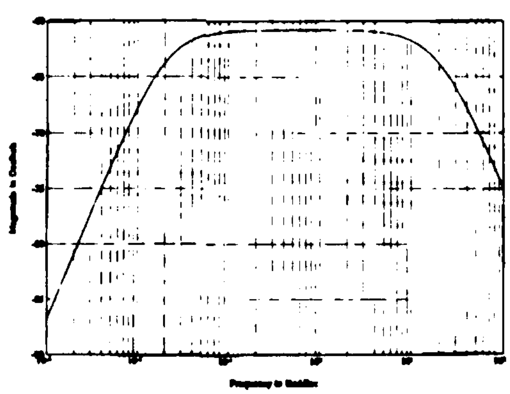

Figure 14: Frequency Response of System Designed for a Long Time Constant

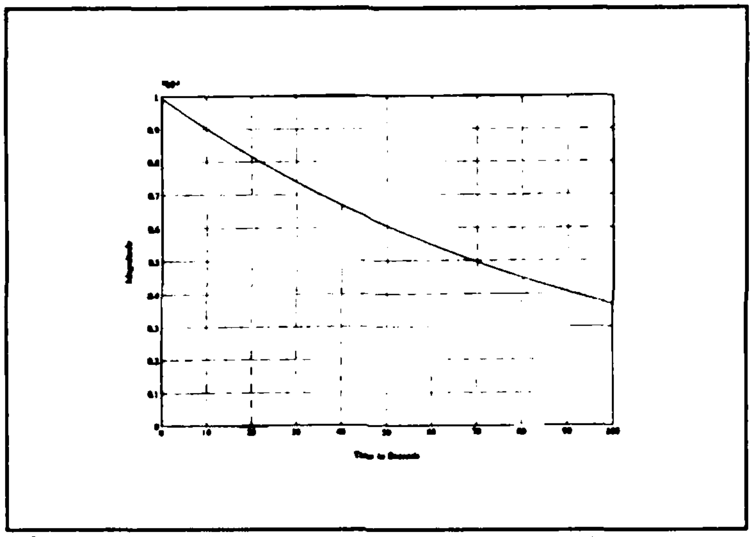

Figure 13: Step Response of System Designed for Long Time Constant

value of the feedback capacitor determines the gain. The lower the value of the feedback capacitor, the higher the gain; but the lower the feedback capacitor, the shorter the time constant. This relationship suggests that a large feedback resistor must be used to achieve a satisfactorily long time constant and high gain. Unfortunately, too large a feedback resistor will cause a high offset current, which is detrimental to the circuit. Should the amplifier be designed for a long time constant (see Figures 13 and 14) or a large gain (see Figures 15 and 16)?

Obviously both of these solutions are unsatisfactory. The first design's gain is too small to be used by the computer equipment available. The second

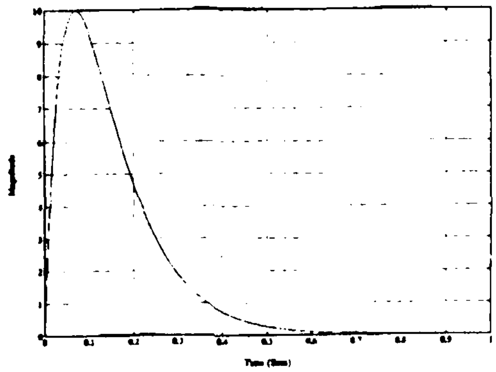

Figure 15: Step Response of System Designed for a High Gain

design's time constant is so fast that signals would die too quickly for the computer to make useful calculations. It should also be noticed that the high gain is *not* constant. It depends upon the frequency of the input.

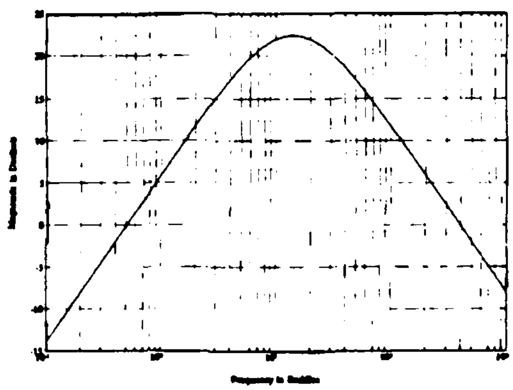

Figure 16: Frequency Response of System Designed for High Gain

Most optimization starts with a premise on what the system is to accomplish. First, a time constant of 1 second was considered large enough for the computer to acquire a sufficiently accurate reading on the voltage to calculate the force. Also, it was determined that each cell on the film could produce around 10 volts. This voltage is more than enough, so a gain of 1 was chosen. These design specifications of time constant and gain made the value of the feedback resistor around 1000 mega ohms and the value of the feedback capacitor around .001 micro-farads. The characteristics of the final solution are better than those of the previous designs (see Figures 17 and 18).

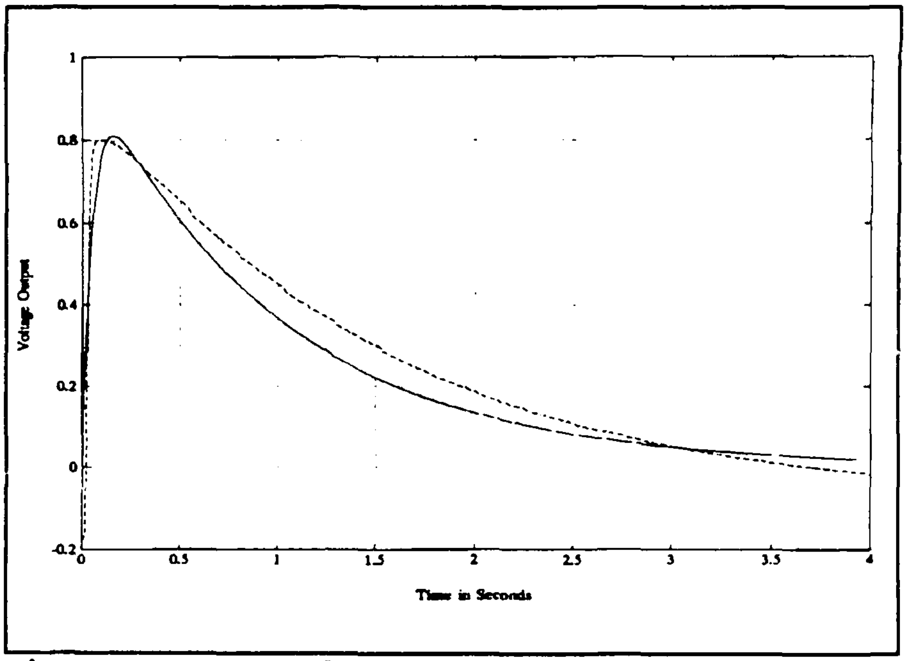

Figure 17: Actual and Expected Step Response of System

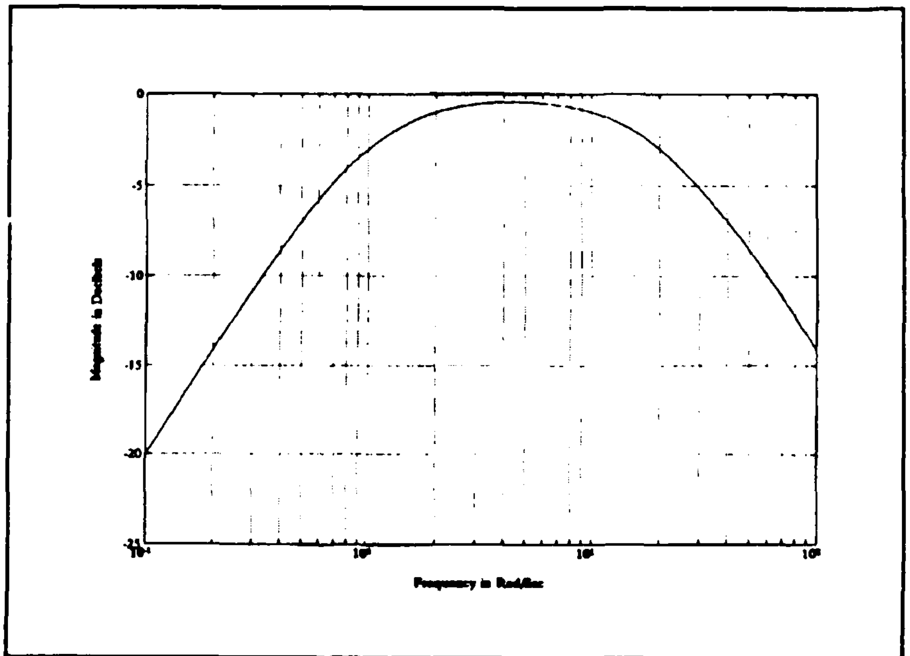

Figure 18: Frequency Response of System

Computer Subsystem

The computer used for the taction system was a standard Zenith 248 with a hard drive, parallel ports, and an A/D,D/A converter. In this project, the computer received analog signals from the signal processor subsystem and then digitized them with an analog to digital converter. After the conversion, the computer will display information concerning the force.

The most important piece of equipment is the DT2801 A/D converter. It has 12-bit resolution, operates at a maximum of 13.7 Khz throughput, works with voltages from -10 to 10 volts, and has a maximum gain of 8. The 12-bit resolution on the -10 to 10 volt scales means that the resolution is around 5 millivolts. With this converter is a software driver, PCLAB; the system has code that will support Turbo Pascal [15].

The first program written was TacGraph. In TacGraph, a graphic display of the voltage waveforms for each channel is provided. The program asks for the starting and ending channel, maximum and minimum voltage, and delay time. It then asks the user to press a key to start the graph. All the channels specified are drawn, while the computer does a small amount of delay work,

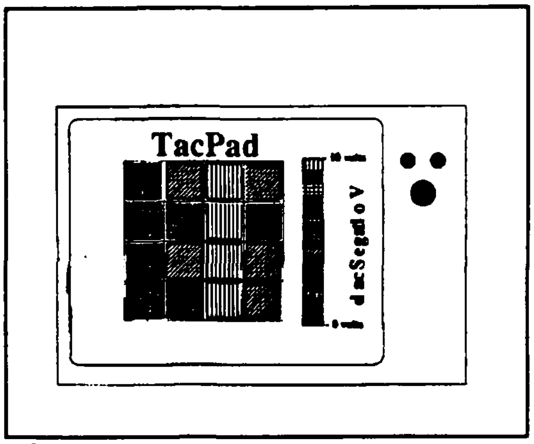

Figure 19: Sample Screen Output for TacPad

depending on the size of the delay time that the user inputs. The larger the delay time the longer the wait between drawing the points. Other versions of TacGraph include ways to write these data to a text file and also to inquire from the computer the length of time that the computer has been taking data. This information is useful to verify the mathematical models in Appendix 1.

The second program is TacPad (see Figure 19). TacPad displays the data from every channel on a grid that represents the tactile sensor subsystem. When an element of the pad is activated, the corresponding element in graphic representation also lights up in a color code. The color corresponds to the amount of voltage produced by the element and is therefore related to the amount of force applied to the sensor. If an object is placed on the tactile sensors, a rough outline of the shape of the object is visible. The palette of the computer was changed so that the color change would be pleasing to the eye. A detailed listing of the two Pascal programs is in Appendix 3.

Conclusions

Through the design and testing of this project, it has been demonstrated that taction systems relay information about the exerted force, the shape, and size of the object. Taction systems are unique because they contact the object and communicate information about the part of the object that is in the end effector of the robot. This information is often not retrievable by any other system. This information could be utilized to make the tasks easier for the robot to accomplish.

Though there were many problems in the development of this taction system, the qualities of this film overshadow these problems. Mathematical models for the film's response are representative of the actual output of the film. Construction techniques have been devised that eliminate most of the problems associated with the film. Since these problems have been worked out, there is no reason why these inexpensive, small, sensitive devices should not be used in further research and development of taction systems at the Naval Academy.

Future Applications

The first application is to install a taction system on a Heath robot. Consequently, the sensor will be limited in size and weight. The size of the current end effector on the Heath robot is 1 X 1/2 inches. This is a very small area in which to fit a multi-sensor taction device. The end effector could be enlarged, but any increase in the size may adversely affect the weight of the end effector. The weight or size of the sensor cannot get so large that it hampers the robot in its ability to do its assigned task. It is possible, however, to make the sensors smaller. The major problem will be etching the film into small element arrays. One method would be to find a protective laminate that could be applied to the film so that the etching is not needed and the entire film could be immersed in the sodium hydroxide solution. But the laminate would either have to be removed or be able to conduct electricity. No substance is known that could laminate the film in this manner. A more feasible idea is the use of pen plotter, some of which have very high resolution. It would be possible to take a pen from a pen plotter and replace the ink with a solution of the sodium hydroxide solution. Then the pattern could be etched repeatedly by the pen plotter. Another alternative would be to buy pre-made tactile grids from the Pennwalt corporation but this alternative would be expensive and unnecessary if either of the first two techniques worked.

After the taction system is installed, many different applications for the robots are possible. Pattern recognition of objects should be much simpler with the taction system than with the vision system. Extensive programs could be made to integrate the vision system and the taction system into a comprehensive sense system for the robot. Artificial Intelligence programs could be made to use information from the taction system. This approach opens a new, exciting field for the robotics lab at USNA.

References

1. Kynar Piezo Film Technical Manual, Pennwalt Corporation, 1987.

2. Harmon, L.D., "Automated Tactile Sensing," International Journal of Robotics Research, Vol. 1, No. 2 (Summer 1982), pp. 1-32.

3. Harmon, L.D., "Automated Touch Sensing: A Brief Perspective and Several New Approaches," I.E.E.E. International Conference On Robotics, Vol 1. (March 1984), pp. 326-331.

4. Klafter, R.D., Chmeimlewski, T.A., and Negin, M., Robotic Engineering An Integral Approach, Prentice-Hall, Inc, 1989.

5. Hill, J.W., and Sword, A. J., "Manipulation Based on Sensor-Directed Control: An Integrated End Effector and Touch Sensing System," Proceedings of the 17th annual Human Factors Society Convention, Washington D.C., October 1973.

6. Winger, J.G., and Lee, K.M., "Experimental Investigation of a Tactile Sensor Based on Bending Losses In Fiber Optics," I.E.E.E International Conference on Robotics and Automation, Vol. 2, (April 1988), pp. 754-759.

7. Tise B., "A Compact High Resolution Piezoresistive Digital Tactile Sensor," I.E.E.E. International Conference on Robotics and Automation, Vol. 2, (April 1988), pp. 760-764.

8. Grahn, A.R,. and Astle, L., "Robotic Ultrasonic Force Sensor Arrays", Proceedings of the Robots 8 Conference - Application for Today, Vol 2. Detroit, Mich., June 4-7, 1984. Dearborn, Mich.: Society of Manufacturing Engineers, 1984, pp 21-1 to 21-17.

9. Dario, P., and Buttazzo, G., "An Anthropomorphic Robot Finger for Investigating Artificial Tactile Perception," International Journal of Robotics Research, Vol. 6, No. 3, (Fall 1987), pp. 25-48.

10. Dario, P., and Bergamasco, M., "An Advanced Robot System for Automated Diagnostic Tasks Through Palpation," I.E.E.E. Transaction on Biomedical Engineering, Vol. 35, No. 2 (February 1988), pp. 118-126.

11. Miler, C., Little, J., Bangert, S., PC-Matlab, The MathWorks, Inc, 1987.

12. Dario, P., Bomenici, C., Bardelli, R., De Rossi, d., and Pinotti, P.C., "Piezoelectric Polymers: New Sensor Material For Robotic Applications," Proceedings of the 13th International Symposium on Industrial Robots and Robots 7, vol 2, Chicago, April 1983, pp. 1434 to 14-49.

13. Kynar Piezo Film Application Notes, Pennwalt Corporation, Number 20.

14. Burrucker, E.F., ES402 Technical Manual, September 1984.

15. User Manual for Dt2801 Series, Data Translation, Inc. 1987.

Appendix 1
Mathematical Formulas

In Figure 20, the film has not been connected to any circuitry. The resistance of the film is large; it can be modeled as an open circuit. Then the voltage produced by the film is dependent upon the capacitance of the film. Q is the charge produced by the applied force and c_{film} is the capacitance of the film.

$$V_o = \frac{Q}{C_{film}}$$

Connecting a circuit causes a change is the model (Figure 21). In this case, the R_{film} and C_{film} is the resistance and capacitance of film and the connecting circuitry. The Laplace operator is s. The transfer function is shown below.

$$\frac{V_o(s)}{Q(s)} = \frac{\frac{1}{C_{film}}}{s + \frac{1}{R_{film} C_{film}}}$$

In Figure 7, the frequency response of the film is shown. The frequency where the graph hits the -3 db point is called the break point frequency, f_c. It is calculated below.

$$f_c = \frac{1}{2\pi R_{film} C_{film}}$$

In figure 10, the charge amplifier will cancel the effect of the connecting cable capacitance. The E_i and

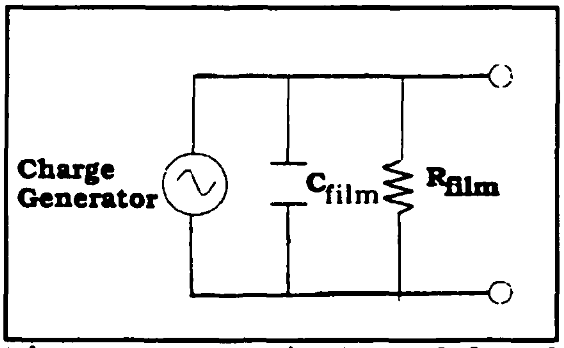

Figure 20: First Model of Film

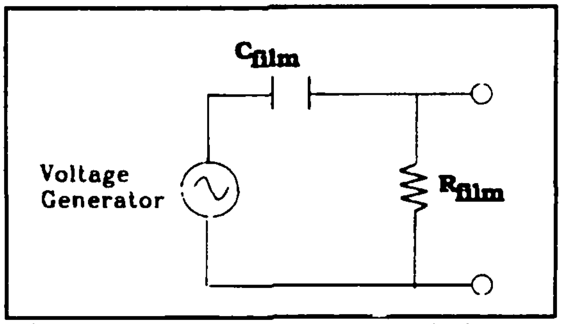

Figure 21: Second Model of Film

the E_o are the voltage in and out of the charge amplifier. The current into the charge amplifier is I_i and the input impedance is Z_i. C_f is the feed back capacitance. The gain of the amplifier is A.

$$E_o(s) = -AE_i(s)$$

$$\sum I=0, I_i(s)+E_o(s)C_f s=0$$

$$\sum i=0, I_i(s)-AE_i(s)C_f s=0$$

$$Z_i(s)=\frac{E_i(s)}{I_i(s)}=\frac{1}{AC_f s}$$

The internal impedance is small. This would make the amplifier seem like a large capacitor. The smaller capacitance of the film and connecting cable have minimal effect.

The transfer function for figure 10 is shown below. It is derived by nodal analysis.

$$\sum i=0, E_i(s)C_i s-E_o(s)C_f s-\frac{E_o(s)}{R_f}=0$$

$$\frac{E_o(s)}{E_i(s)}=\frac{\frac{C_i}{C_f}s}{s+\frac{1}{R_fC_f}}$$

But this model does not take into count the time constant of the film. To get good models such as the ones in figure 17, an extra pole was added.

$$\frac{E_o(s)}{E_i(s)}=\frac{\frac{1}{C_{film}}\frac{C_i}{C_f}s}{(s+\frac{1}{R_{film}C_{film}})(s+\frac{1}{R_fC_f})}$$

In figure 12, the resistor in the feedback loop is removed. Care must be taken to insure that the amplifier does not go unstable; without the resistor the amplifier is an integrator.

$$\frac{E_o(s)}{E_i(s)}=\frac{\frac{1}{C_{film}}\frac{C_i}{C_f}s}{s(s+\frac{1}{R_{film}C_{film}})}$$

Appendix 2
Construction of Tactile Sensor

The tactile sensor construction includes all piezoelectric film etching, all lead attachment, and the connection of these leads to a male pin. It is assumed that the tactile array will have 16 elements, but any increase in the number of channels will not cause any large problems. Only the number of leads and the size of the male pin will have to change. To build a taction device, these are the parts needed:

(1) Conductive Epoxy, Tra-Duct 2902, Tra-Con Industries;
(2) Piezoelectric Film Sheet, 110 micro-meter thickness, Pennwalt Corporation, Kynar Piezo Film Department;
(3) Thin wire leads, either small gauge wire wrap or ribbon cable;
(4) 34 pin male connector for ribbon cable, (more pins needed if higher number of channels);
(5) Metal base, 1/4 inch Al or thicker;
(6) Non-Conductive Rubber;
(7) Non-Conductive Protective Plastic Sheet;
(8) Sodium Hydroxide, 6 molar or greater.

Care must be exercised when handling the PVDF. Clean rubber gloves should be worn to avoid contaminating the film. First, it is necessary to make separate cells on the piezoelectric film. This is done one of two ways.

Method 1. Place piece of film to be etched on a pen plotter. With a pen filled with sodium hydroxide solution, etch the pattern wanted in the film. Place film in distilled water to remove the sodium hydroxide residue. Let film dry.

Method 2. Cut out pieces of film about twice the size of the cell size. Attach leads to individual sensors first (see next section). Then place the edges of the film in around one cm deep of the sodium hydroxide solution. This procedure will to take the metallization off around edges of the film. Place film in distilled water to remove any sodium hydroxide residue.

Next the leads should be attached. Clean dry film is needed for the conductive epoxy to be effective. The film should be dry and clean from the manufacturers but if not, place the film in distilled water and gently rub the film with a cotton ball. Then let the film air dry.

Cut out pieces of metal foil the same size as the tactile cells. Follow instruction to prepare the conductive epoxy, taking care to knead the contents of the epoxy packet well to ensure the best qualities of the epoxy. Apply a small amount of epoxy to the foil and press the foil/epoxy onto the cell with the wire lead between the foil and the piezoelectric cell. Make sure that no epoxy bleeds over to the surrounding cells. Also make sure to leave enough wire to travel to the pin connector. Place cell under a weight, such as a book, and let the epoxy dry for about 24 hours. It takes 72 hours for the entire curing process, so care should be taken when handling the tactile cell during this time.

The metal base, plastic sheet, piece of metal foil, and non-conductive rubber should all be the same size and should have screw holes to attach them together. The tactile sensor grid (method 1), or the cells (method 2) ground side should be attached on the metal base with a thin coating of conductive epoxy. Allow 24 hours drying time just as before. The leads should be run between the individual cells to prevent their interference upon the activation of the cell. Tack the leads down with normal tape or epoxy. Next place the protective sheet over the tactile sensor grid and attach it to the base with normal epoxy. Make sure that the holes line up. Place conductive foil over plastic sheet and electrically ground it by connecting it to the base which is also at ground. This should effectively shield the sensor from electro-magnetic waves. Then place the non-conductive rubber over the metal foil and bolt the entire taction pad together. The wires can be wire wrapped or soldered to the male pin connector. Care must be taken to make the wires as short as possible outside the shielding of the taction pad. If the leads have to be long, consider shielding the film with grounded foil or using small coaxial cable. Shielding is a problem until the signal reaches the signal processor. After the signal processor, shielding is no longer a problem.

Construction of Signal Processor

The first wire on the ribbon cable (connected to the male pin) is channel zero, then ground, channel 1, ground, channel 2, ground, etc. This goes into a male pin which is on a pc board. For the construction of the charge amplifier, a 1000 mega-ohm resistor and a 0.001 micro-farad capacitor was used. These values are close to the values needed by any PVDF sensor but it is best to experiment with different values on the bread board in order to pick the best values for the feedback capacitors and resistors for the particular tactile sensor used.

The capacitance and resistance of the film are dependent on the size of the cells. Measure the capacitance and resistance of the tactile cells. Choose a capacitor and resistor so that the gain and time constant are both around one (see mathematical formulas in Appendix 1). Then bread board the amplifier (TL084C) and observe the output of the charge amplifier as the cell is activated on an oscilloscope. Make sure to activate the cell as hard as possible to get a good voltage range from the tactile device because the voltage cannot exceed 10 volts or it will exceed the limit of the A/D converter. If the voltage does exceed 10 volts change the values of the feedback resistor and capacitor to maintain the time constant but lower the gain. When a satisfactory design is finally reached, place chips and components on a pc board and begin the soldering process. It is nice to mount the pc board in a shielded box with its own power supply.

Appendix 3

Program TacPad;

```
(*************************************************************)
(***  Program     :  TacPad                              ***)
(***  Author      :  Lyle Edward Hoag                    ***)
(***  Date        :  27 Apr 1990                         ***)
(***  Description :  This program will display the       ***)
(***  voltages from the any of the 4 x 4 or 16 element   ***)
(***  tactile grids to the screen.  A 14 color scale will ***)
(***  be the guide to how hard the individual cells are  ***)
(***  compressed.  The elements will be refreshed at the ***)
(***  maximum speed of the A/D converter.  There will be a ***)
(***  4 x 4 grid placed on the screen and each cell on the ***)
(***  will correspond to one cell on the tactile sensor.  ***)
(*************************************************************)

(*************************************************************)
(***  Tacpad uses a number of pre-written library's.  The  ***)
(***  first three - Graph, Crt, Dos - are common libraries ***)
(***  available with turbo pascal.  The last two - Pcldefs,***)
(***  Pclerrs - are PCLAB libraries for the A/D converter. ***)
(*************************************************************)

uses
  Graph,
  Crt,
  Dos,
  Pcldefs,
  Pclerrs;

(*************************************************************)
(***  Colortype is for the different colors.  It will be   ***)
(***  used to change the basic palette to a user palata. ***)
(***  Voltagetype is just an array where the voltages of   ***)
(***  on sweep of the tactile pad are stored.              ***)
(*************************************************************)

type
  colortype = array[0..15] of integer;
  voltagetype = array[0..15] of real;

(*************************************************************)
(***  Most of these constants deal with the drawing of the ***)
(***  taction pad or the voltage scale on the screen.      ***)
(*************************************************************)

const
  x1         = 120;  (*** Right Side of Taction Pad Grid ***)
  x2         = 480;  (*** Left Side of Taction Pad Grid  ***)
  x3         = 510;  (*** Right Side of Color Scale      ***)
  x4         = 540;  (*** Left Side of Color Scale       ***)
  y1         = 40;   (*** Top of Taction Pad Grid        ***)
  y2         = 308;  (*** Bottom of Taction Pad Grid     ***)
  xdiff      = 90;   (*** Size of Cube in x              ***)
  ydiff      = 67;   (*** Size of Cube in y              ***)
  ydiff2     = 18;   (*** Size of Color Scale in y       ***)
  gain       = 1;    (*** Gain for Each A/D Channel      ***)
  nochannels = 16;   (*** Number of Channels             ***)

(*************************************************************)
```

```
var
  Gd       : integer;  (*** Graphic Routine Error Variable ***)
  Gm       : integer;  (*** Graphic Routine Error Variable ***)
  Counter  : integer;
  Row      : integer;  (*** Row of Tacpad                  ***)
  Column   : integer;  (*** Column of Tacpad               ***)
  Errorcd  : integer;  (*** A/D Routine Error Variable     ***)
  Chan     : integer;  (*** Channel Number                 ***)
  Adata    : word;     (*** Number from A/D converter      ***)
  Palata : paletteType;(* New Palata of Colors          ***)
  Collor   : colortype;(*** New Colors                     ***)
  Cvolts   : voltagetype;(* Array of Tacpad voltages       ***)

(*****************************************************************)

begin
  (***  Graphics Initiation  ***)
  Gd := Detect;
  InitGraph (Gd, Gm, '');
  if GraphResult <> grOk then
  Halt(1);

  (***  Making New Palata ***)
  with Palata do
  begin
    Size:= 16;
    Colors[0] := 0;   (***  Black         ***)
    Colors[1] := 8;   (***  Dark Gray     ***)
    Colors[2] := 1;   (***  Blue          ***)
    Colors[3] := 9;   (***  Light Blue    ***)
    Colors[4] := 11;  (***  Light Cyan    ***)
    Colors[5] := 13;  (***  Light Magenta ***)
    Colors[6] := 3;   (***  Cyan          ***)
    Colors[7] := 2;   (***  Green         ***)
    Colors[8] := 10;  (***   Light Green  ***)
    Colors[9] := 7;   (***  Light Gray    ***)
    Colors[10] := 14; (***  Yellow        ***)
    Colors[11] := 6;  (***  Brown         ***)
    Colors[12] := 5;  (***  Magenta       ***)
    Colors[13] := 12; (***  Light Red     ***)
    Colors[14] := 4;  (***  Red           ***)
    Colors[15] := 15; (***  White         ***)
    SetAllPalette (Palata);
  end;

  (*** Initial Graphics Text  ***)

  SetTextJustify (CenterText, CenterText);
  SetTextStyle (TriplexFont, HorizDir,4);
  OutTextXY (300, 20, 'TacPad');

  SetTextStyle (DefaultFont, HorizDir, 1);
  SetTextJustify (LeftText, CenterText);
  OutTextXY (550, y1, '--10 volts');
  OutTextXY (550, y1 + ydiff2 * 15 + 1, '--0 volts');

  SetTextJustify (CenterText, CenterText);
  SetTextStyle (TriplexFont, VertDir, 2);
  OutTextXY (550, y1 + ydiff2 * 7, 'Voltage Scale');

  (***  Initial Graphic Draw  ***)

  Setcolor (15);
  Rectangle (x1, y1, x2, y2);   (***  Draws Large Square  ***)
```

```
  (***  Draws Lines to Make the Grid  ***)
  for Counter := 1 to 3 do
  begin
    line (x1 + Counter * xdiff, y1, x1 + Counter * xdiff, y2);
    line (x1, Counter * ydiff + y1, x2, Counter * ydiff + y1);
  end;

  (***  Draws Initial Color Scale Next to TacPad  ***)
  for Counter := 0 to 14 do
  begin
    Setfillstyle (1, Counter);
    Bar3d (x3, y1 + ydiff2 * (14 - Counter), x4,
           y1 + ydiff2 * (15 - Counter), 0, false);
  end;

(***  A/D Part of Program                        ***)

(***  Initialize A/D Converter  ***)

  Errorcd := 0;
  Errorcd := Set_Error_Control_Word (Errorcd);

  repeat
    for Chan := 0 to nochannels - 1 do
    begin
      Errorcd := Adc_Value (Chan, gain, Adata);
      (***  Adata is a number between 0 and 4096  ***)
      Errorcd := Analog_To_Volts (Adata, gain, Cvolts[Chan]);
      (***  Cvolts is a voltage that corresponds to Adata  ***)
      Collor[Chan] := Abs (Round (1.4 * Cvolts[Chan]));
      (***  Collor now has an integer between 0 and 14 that ***)
      (***  corresponds to a voltage in the A/D Converter.  ***)
    end;

    (***  Graphics Routine that fills in the grid with the  ***)
    (***  with the corresponding color.                     ***)

    Counter := 0;  (*** Increments Channels  ***)
    for Row := 0 to 3 do
      for Column := 0 to 3 do
      begin
        Setfillstyle (1, Collor[Counter]);
        Bar(x1 + xdiff * Column + 1, y1 + ydiff * Row + 1,
            x1 + xdiff * (Column + 1) - 1, y1 + ydiff * (Row + 1) -1);
        inc (Counter);  (***  Next Channel  ***)
      end;
  until Keypressed;
  Closegraph;
end.

(*****************************************************************)
```

Program TacGraph (Input, Output);

```
(*****************************************************************)
(***  Program     :  TacGraph                                 ***)
(***  Author      :  Lyle Edward Hoag                         ***)
(***  Date        :  27 Apr 1990                              ***)
(***  Description :  This program will display the            ***)
(***  voltages from the any of the cells in the Tactile       ***)
(***  grid in its wave form.  13 colors are used for the      ***)
(***  different channels.  This is because of on the black    ***)
(***  background some colors don't come out as good. The      ***)
(***  program pulls values at the maximum speed of the A/D    ***)
(***  converter with a user delay.  In other versions, it     ***)
(***  is possible to export the values to a textfile and      ***)
(***  tell the amount of time that has passed between         ***)
(***  data sets.  This is useful for experimental data to     ***)
(***  verify expected results.                                ***)
(*****************************************************************)

(*****************************************************************)
(***  TacGraph uses a number of pre-written libraries. The     ***)
(***  first six -  Error, Getbgi, Ctrnsfrm, GetInput, Utils***)
(***  Realtype - are written by David F. Clipsham for his     ***)
(***  trident project.   The next three - Graph, Crt, Dos -***)
(***  are common libraries available with turbo pascal.  The***)
(***  last two - Pcldefs, Pclerrs - are PCLAB libraries for***)
(***  the A/D converter.                                      ***)
(*****************************************************************)

uses
  Error,
  Getbgi,
  Ctrnsfrm,
  Getinput,
  Utils,
  Realtype,
  Graph,
  Crt,
  Dos,
  Pcldefs,
  Pclerrs;

(*****************************************************************)
type
  sttype = string[3];

(*****************************************************************)
const
  Nochannels = 16;
  Gain = 1;

(*****************************************************************)
var
  Delaytime : integer;  (*** User Delay Variable              ***)
  BeginChan : integer;  (*** User Entry Channel               ***)
  EndChan   : integer;  (*** User Exit Channel                ***)
  Resp      : char;     (*** User Response                    ***)

(*****************************************************************)
(***  Procedure AskScale ask for scale on the graph, and      ***)
(***  other user inputs.                                      ***)
(*****************************************************************)
```

```
procedure askscale(var largeY: sttype;
                   var smallY: sttype);

  var
    rsp:char;
    miny,maxy:float;

  begin
    install_bgi;  (***  Written by D.F Clipsham -- I don't ***)
                  (***  know what this does, but it works. ***)
    clrscr;
    write('Min Y: ');
    readln(miny);
    str(Miny:2:1,SmallY);
    write('Max Y: ');
    readln(maxy);
    str (Maxy:2:1,LargeY);
    write('Delay Constant: ');
    readln(delaytime);
    write ('Begin At Channel: ');
    readln (beginchan);
    write ('End At Channel: ');
    readln (EndChan);

   makeworld(0,miny,600,maxy);(***  This is some coordinate ***)
   makewindow(30,40,630,345,0,0);(***  transformations.     ***)
   makescalefactors;
   clrscr;

   cwritexy(25,12,cyan,red,'Press Any Key to Begin...');
   tcol(lightgray,black);
   rsp:=readkey;
 end;


 Procedure initialize(largeY, smally:sttype);

   const
     gd:integer = EGA;
     gm:integer = EGAHi;
   var
     Palette : paletteType;


   begin
     initgraph(gd,gm,'');
     setviewport(0,0,getmaxx,getmaxy,clipon);
     (***  Sets Writing Area of Screen  ***)
     setcolor(white);
     line(30,40,30,345);    (*** Draw Y axis                    ***)
     windowline(0,0,620,0); (***  Procedure by D.F. Clipsham  ***)
                            (***  Draws a line for the X axis ***)

   (***  Making New Palette ***)
   with Palate do
   begin
     Size:= 16;
     Colors[0] := 0;   (***  Black         ***)
     Colors[1] := 8;   (***  Dark Gray     ***)
     Colors[2] := 1;   (***  Blue          ***)
     Colors[3] := 9;   (***  Light Blue    ***)
     Colors[4] := 11;  (***  Light Cyan    ***)
     Colors[5] := 13;  (***  Light Magenta ***)
     Colors[6] := 3;   (***  Cyan          ***)
     Colors[7] := 2;   (***  Green         ***)
```

```
    Colors[8] := 10;  (***  Light Green    ***)
    Colors[9] := 7;   (***  Light Gray     ***)
    Colors[10] := 14; (***  Yellow         ***)
    Colors[11] := 6;  (***  Brown          ***)
    Colors[12] := 5;  (***  Magenta        ***)
    Colors[13] := 12; (***  Light Red      ***)
    Colors[14] := 4;  (***  Red            ***)
    Colors[15] := 15; (***  White          ***)
    SetAllPalette (Palata);
  end;
    (*** Doing Text ***)
    SetTextJustify (CenterText, CenterText);
    SetTextStyle (TriplexFont, HorizDir,4);
    OutTextXY (300, 15, 'TacGraph');

    SetTextStyle (DefaultFont, HorizDir, 1);
    SetTextJustify (LeftText, CenterText);
    OutTextXY (3, 40,LargeY);  (***  Writes the scale  ***)
    OutTextXY (3, 345, SmallY);(***  Writes the scale  ***)
  end;

(****************************************************************)
(***  Procedure Plotpoints plots the separate points in the***)
(***  graph.                                              ***)
(****************************************************************)
procedure plotpoints;

var
  errorcd :  integer;
  adata   :  word;
  cvolts  :  real;
  x,chan  :  integer;
  rsp     :  char;
  counter :  integer;

begin
  errorcd:=0;
  errorcd:=set_error_control_word(errorcd);
  for x:=0 to 620 do
  begin
    counter := 3;
    for chan:=BeginChan to EndChan do
    begin
      errorcd:=adc_value(chan,gain,adata);
      errorcd:=analog_to_volts(adata,gain,cvolts);
      windowpoint(x,cvolts,point_sym,counter,1);
      (***  Windowpoint is a D.F.C. coordinate tranform ***)
      inc (counter);
      If counter = 16 then counter := 3;
    end;

    for chan:=1 to delaytime do (*** this it useless delay work ***)
    begin
      cvolts:=sin(30)/sin(10);
    end;
  end;
  rsp:=readkey;
  closegraph;
end;

(****************************************************************)
(****                    MAIN PROGRAM                       ****)
(****************************************************************)

var
```

```
  LargeY  : sttype;
  SmallY  : sttype;
  resp1   : char;

begin
  askscale(LargeY, SmallY);
  repeat
    initialize (LargeY, SmallY);
    plotpoints;
    clrscr;
    writeln('Another Run? (Y/N)');

    repeat
      resp:=readkey;
    until upcase(resp) in ['Y','N'];

    if upcase(resp) = 'Y' then
    begin
      writeln('Re-Initialyze Graph? (Y/N)');

      repeat
         resp1 := readkey;
      until upcase(resp1) in ['Y', 'N'];

      if upcase(resp1) = 'Y' then Askscale (LargeY,SmallY);
    end;
  until upcase(resp)='N';
  clrscr;
end.
(****************************************************************)
```